Binary Paths to Type Ia Supernovae Explosions
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Survey for the Binary Progenitor in SN1006 and Update on SN1572

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Abstract. We have completed a survey down to R = 15 mag of the stars within a circle of 4 arcmin radius around the nominal center of the remnant of SN 1006, one of the three historical Type Ia supernovae (the other two being SN 1572 and SN 1604), in search of a possible surviving binary companion of the white dwarf whose explosion gave rise to the supernova. The stellar parameters (effective temperature, surface gravity, and metallicity), as well as the radial velocities of all the stars, have been measured from spectra obtained with the UVES spectrograph at the VLT, and from the former and the available photometry, distances have been determined. Chemical abundances of the Fe-peak elements Cr, Mn, Co, and Ni have also been measured to check for possible contamination of the stellar surface by the supernova ejecta. The limiting magnitude of the survey would allow us to find stellar companions of the red-giant type, subgiant stars, and main–sequence stars down to F5–6. Unlike in SN 1572, where a subgiant of type G0–1 has been proposed as the companion of SN 1572, for SN 1006 we can discard the possibility that SN 1006 had a red giant or subgiant companion.

Keywords. stars: abundances, supernovae — supernova remnants

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1. Background

Type Ia supernovae (SNe Ia) have led to the discovery of the acceleration of the expansion of the Universe. Their empirical properties are well known but their progenitors are under debate. Since SNe Ia are believed to take place in a binary system where the companion (a red giant, a subgiant or a main sequence star) feeds the white dwarf until explosion, we can investigate the progenitor system by a direct approach and survey the field of historical SNe Ia in search of the surviving companion. The latter strategy has been followed for SN 1572, using the observatories at La Palma, Lick, and Keck (Ruiz-Lapuente *et al.* 2004). The stars appearing within the 15% innermost area of the remnant of SN 1572 (0.65′) were observed both photometrically and spectroscopically at multiple epochs over seven years. The proper motions of these stars were measured as well, using images obtained with the WFPC2 on board the *Hubble Space Telescope* (*HST*) (GO–9729). The results revealed that many properties of any surviving companion star of SN 1572 were unlike those predicted by hydrodynamical models. For example, the surviving companion star (if present) could not be an overluminous object nor a blue star, as there were none in that field. Red giants and He stars were also discarded as possible companions in SN 1572.

A subgiant star with metallicity close to solar and moving at high speed for its distance was suggested as the likely surviving companion of the exploding white dwarf (WD) that produced SN 1572 (Ruiz-Lapuente *et al.* 2004). This star, denoted Tycho G, has coordinates $\alpha = 00^{\rm h}25^{\rm m}23.7^{\rm s}$ and $\delta = +64°08'02''$ (J2000.0). Comparisons with a Galactic model showed that the probability of finding a rapidly moving subgiant with solar metallicity at a location compatible with the distance of SN 1572 was very low. A viable scenario for the Tycho SN 1572 progenitor would be a system resembling the recurrent nova U Scorpii. González Hernández *et al.* (2009) resolved some questions regarding the metallicity and spectral classification of Tycho G. The chemical composition of the star and the stellar parameters as derived from new data showed that Tycho G might have suffered Ni pollution by the supernova. The Ni abundance was measured to be [Ni/Fe] = 0.16 ± 0.04, well above the value in thin–disk and thick–disk stars at that metallicity (see Figure 1).

In the survey in SN 1006, we have followed similar steps as in SN 1572 but using UVES at the VLT to get the stellar parameters and the abundance patterns of stars inside the 20% of radius of the supernova remnant. The remnant is 1,005 yr old and nearer to us than SN 1572. Those are the reasons for covering a much larger radius in the search than in SN 1572. The distance to SN 1006 has been determined through the expansion velocity and the proper motions of the ejecta (Winkler, Gupta and Long 2003). They obtain a distance of d = 2.17 ± 0.08 kpc to SN 1006. We centered our search at the center proposed by Allen *et al.* (2001) as the likely center of the remnant. This center is at $\alpha = 15^{\rm h}2^{\rm m}55^{\rm s}$, $\delta = -41°55'12''$. Winkler *et al.* (2005) have studied the structure of the supernova remnant as inferred from observations of absorption spectra of five background objects. As they show in their Figure 8, the outer shell is not seen face–on but with the

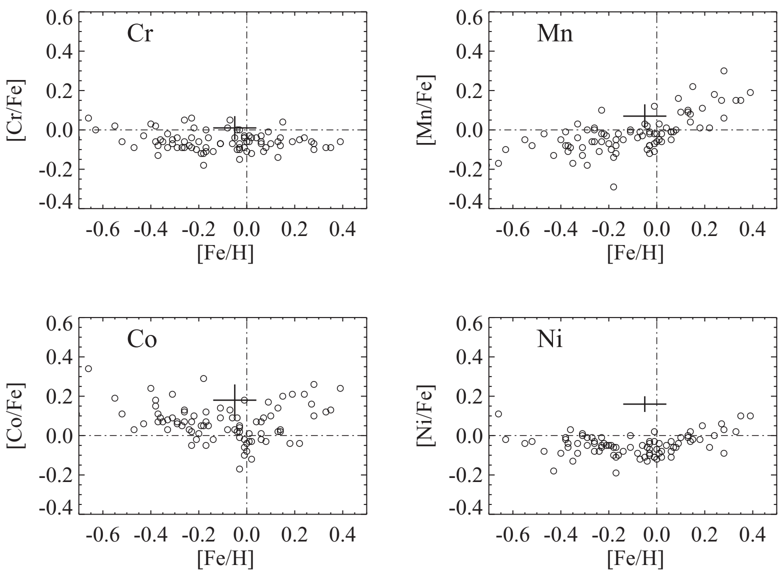

Figure 1. Abundance ratios of Tycho G (wide cross) in comparison with the abundances of G and K metal–rich stars. Galactic trends are taken from Ecuvillon *et al.* (2004), Ecuvillon *et al.* (2006), and Gilli *et al.* (2006). The dashed–dotted lines indicate solar abundance values.

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west side towards the observer. In this case the explosion center is displaced from the present center of the shell towards the east. Thus it seems plausible that we have at least 3 arcmin of uncertainty on the center of the explosion. We have to add to it the angular distance that the companion star could have moved according to the velocity that it might have after the explosion. For a star at a distance of d= 2.1 kpc and a velocity perpendicular to the line of sight of 100 km s^{-1} the angular displacement in the sky in 1,005 years since the explosion would be $10''$. This leaves a generous search radius of 4 arcmin for this wide supernova remnant.

The area around the center of the SNR of SN 1006 has been surveyed up to $m_R = 15$. Given the distance to the SNR and adopting an extinction $A_V = 0.3$ mag in its direction, that includes all red–giant stars, all subgiants, and all main–sequence stars hotter than the spectral type F5–6.

2. Implications

Generally, Ni tracks Fe throughout the [Fe/H] range down to [Fe/H] = -1. The average value and scatter found by Reddy, Lambert, & Allende Prieto (2006) is [Ni/Fe] = –0.05 ± 0.02 for thin disk stars and [Ni/Fe] = –0.01 ± 0.04 for thick disk stars. Bensby *et al.* (2005) found [Ni/Fe] = –0.06 ± 0.04 for thin disk stars and [Ni/Fe] = –0.02 ± 0.02 for thick disk stars. For the stars of type G and K, the Ni abundances in Gilli *et al.* (2006) are consistent with those mentioned values. While we can make the comparison of Tycho G with the [Ni/Fe] trend in Gilli *et al.* (2006), in the case of SN 1006 we have to make it with a trend valid for all types of stars. In this study, we use the data from Neves *et al.* (2009) that shows similar trend of low dispersion for the [Ni/Fe] trend for thin disk and thick disk F–, G–, and K–type stars. The average values in Neves *et al.* (2009) are [Ni/Fe] = 0.02±0.03 for thin– and thick–disk stars. The data of our sample of stars in

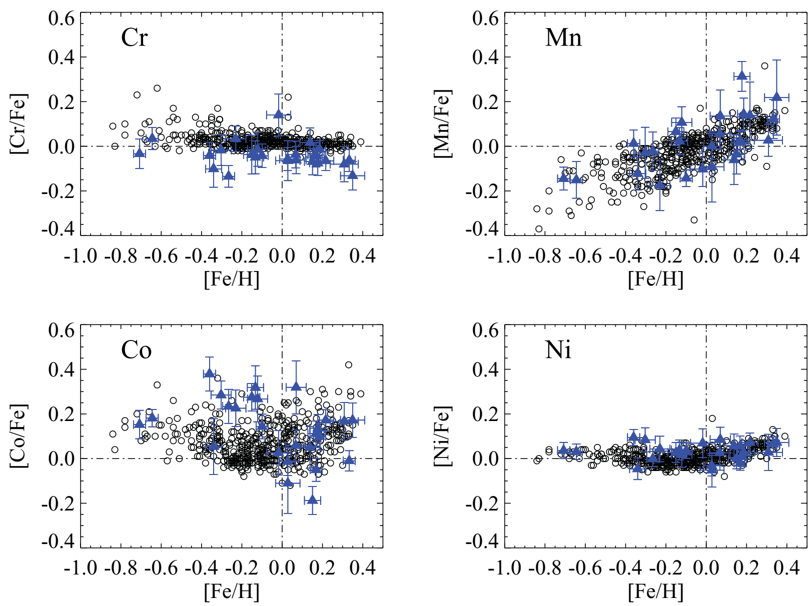

Figure 2. Abundance ratios for the stars in the SN 1006 survey (dark triangles) compared with the Galactic trends from Neves *et al.* (2009) for F–, G–, and K–type stars (open circles).

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SN 1006 do not show any metal enrichment in Ni, Co, Cr or Mn. The spectra of the stars show no peculiarity either.

According to hydrodynamic simulations (Marietta, Burrows, & Fryxell 2000, Pakmor *et al.* 2008, Liu *et al.* 2011), the surviving companion of SN 1006, if it were a red giant, should be at the beginning of the evolution at constant, high luminosity, and given the distance to the supernova remnant, should have been found in our survey. Thus, the observations exclude this kind of companion, either forming a system of the hydrogen Algol type or of the symbiotic type with the white dwarf that exploded. If the companion were a subgiant, it should have been observed showing contamination from the supernova ejecta. We have looked at contamination from the ejecta and found none in SN 1006. In SN 1572, we were able to compare our subgiant candidate with the Galactic trend found for thick and thin disk stars of similar type (within 300K) to that of the subgiant candidate. In that case we found [Ni/Fe] to be 3σ above the trend of stars of similar kind, therefore suggesting pollution by the SN ejecta.

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